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Abstract: A large mode area single-mode optical fiber based on leaky mode filtering has been prepared by modified chemical vapor deposition (MCVD) technique. The fiber has a leaky cladding, which discriminates the fundamental mode from the higher order ones. A preliminary version has 25-µm core diameter and 0.11 numerical aperture. A Gaussian-like mode with 22-µm mode field diameter has been observed after 3-m propagation, in agreement with modeling.

OCIS codes: 060.2430, 060.2280, 060.2330, 060.2410, 060.4005

Introduction

Single-mode Large Mode Area (LMA) fibers are of great interest for high power transportation due to their high threshold of nonlinearities such as stimulated Brillouin scattering, and for the high energy storage capacity in applications such as fiber lasers systems and power-amplifiers for telecommunications. In this aim we address here only solid core optical fibers that can be doped with rare-earth (RE) elements. LMA fibers exist in both the index guidance and photonic bandgap (PBG) guidance principles. Fabrication techniques include MCVD both in index guidance [1] and PBG [2], external direct nanoparticle deposition [3], and air-silica microstructurization based on a so-called “stack-and-draw” process [4]. Generally all these fibers guide several modes causing detrimental instabilities of the output spot shape and beam divergence and pointing [5] in applications where single-mode operation is required. To address this issue, specific set-ups and fibre packaging are used to minimize the power carried by high order modes (HOM) at the expense of reducing the effective fundamental mode area (A_{eff}) or the flexibility of the fiber system. To obtain rigorous single mode operation, irrespective of the fabrication technique, the most difficult specification to meet is the stringent control of the refractive index difference between core and cladding over a large diameter and/or of the cladding microstructure. These stringent specifications impose complex fabrication steps in order to achieve very low core-cladding refractive index difference, and hence a numerical aperture (NA) as low as 0.04 to obtain a really single mode 20 μm-diameter core (at 1064 nm), for example. This is even more difficult when high level of rare earth (RE) ions are added in the core, causing further index elevation. Still, some demonstrations of LMA fibers with record mode area are based on leaky HOM, using only air-silica microstructured fabrication techniques [6]. Form medium size LMA (<1000 μm^2) and medium average laser power, it is interesting to propose a simpler fiber concept and manufacture approach, such as those implementing a CVD process.

Recently, new single mode LMA structures were proposed, which were composed of an otherwise multimode core and a structured cladding acting as a modal filter and guiding through total internal reflection of leaky modes. The cladding structuring may be azimuthal [7,8] or radial [9]. The most relevant parameter allowing effective single mode operation is the strong discrimination between the propagation loss of the fundamental mode and any higher order mode (HOM). The discrimination must be effective within a length of fiber compatible with the expected application. For example, in applications of kilometer-long beam transportations, a 1-dB/km loss on the leaky fundamental mode is acceptable. Instead, for amplifiers and laser applications, a loss less than 0.1 dB/m is acceptable. There are advantages of this type of fiber, because the cylindrical mode geometry (when low birefringence is needed) inherent of this fiber structure is accessible to straightforward CVD fabrication techniques and the imposed fabrication constraints on the size and shape of the core index of refraction are sensibly relaxed. Numerical studies have shown that an effective mode area as large as 1000 μm^2 are achievable in such fibers using a standard fabrication technique such as MCVD [10]. Further, careful design of the cladding structure allows even stronger mode discrimination by implementing resonant coupling of some HOM from the core to the lossy cladding structure [11].

In this paper, we report on the preparation by MCVD and the characterization of an optical fiber designed using the principle detailed in [10]. To experimentally validate the proposed principle, we have designed a simplified refractive index profile (RIP) characterized by two annular, low refractive index trenches in the cladding surrounding a multimode core. We have prepared the fiber, characterized the mode filtering action of the cladding and measured the loss of the fundamental mode. We have observed numerically and experimentally that the effective single mode guidance is achieved beyond 3 meter long propagation.

Design and Analysis

To experimentally validate the principle of operation of the multilayer cladding leaky LMA fiber we proposed a simplified design having only two low index trenches in the cladding region. The proposed design is shown in Fig. 1a: it is designed to operate around the C-band of the telecommunucations. However it could be easily adapted to other spectral windows. The core and other parts with same refractive index (n_1) are of pure silica whereas the low refractive index trenches are doped with fluorine (F). For applications requiring a high rare-earth doping in the core, the refractive index of the core may increase above n_1. However, this increase would not disturb the filtering as long as the HOM effective indices stay lower than n_1, which is easily achievable. n_2 is the refractive index of the zone with highest F-content, in direct contact with the core.

Numerical study on this fiber has been carried out by transfer matrix method (TMM) [12]. TMM is a powerful and convenient method for modal analysis of an optical fiber with arbitrary refractive index profile fiber. In TMM an arbitrary refractive index profile is approximated by a staircase profile by dividing it into a large number of homogeneous layers of sufficiently small thickness. The electric field solutions of scalar wave equation are written in each layer. The field coefficients of the two consecutive layers can be related through a 2×2 matrix by applying suitable boundary conditions at the interface of the two layers. The field coefficients of the first and the last layer of the profile can then be connected by simply multiplying the transfer matrices of all the intermediate layers. Application of suitable boundary conditions in the first and the last layer results in a complex eigenvalue equation. The eigenvalue equation can be solved by a suitable root searching algorithm to obtain complex propagation constant. The real part of the propagation constant gives information about the effective indices of the modes while leakage losses can be calculated by the imaginary part. For the proposed fiber structure the leakage losses of the modes increase with their mode number. It is therefore sufficient to calculate the leakage losses of the first two modes LP_{01} and LP_{11} for the determination of the single-mode condition. The leakage losses of the LP_{01} and LP_{11} modes of the fiber proposed in Fig. 1a have been calculated to be 0.35 dB/m and 8.3 dB/m. The simulated results suggest that the fiber should filter out higher order modes after propagation of 2.4 m and should show single mode operation. The mode field diameter has been calculated to be 26 μm.

Fabrication and characterization

A preform with diameter 11.4 ± 0.2 mm was fabricated by MCVD and drawn into a 110.0 ± 0.2 μm-fiber. The refractive index profile of the drawn fiber, measured with a S14 apparatus (NetTest), is shown in Fig. 1b. The relative refractive index difference $\Delta_1 \sim (n_1 - n_2)/n_1 = 0.28\ \%$ at 1.55 μm ($n_1 = 1.444$) is relatively low. The fluorine concentration could be increased to obtain $\Delta \sim 0.5\ \%$ (by MCVD). Plasma Chemical Vapour Deposition could also be used to increase Δ up to 2 %. The diameter and the numerical aperture of the core, bounded by the first trench with index n_2, are 25.4 ± 0.3 μm and 0.11 ± 6%, respectively. It may be noted that the numerical aperture is relatively high for a single mode LMA fiber. With such characteristics, the normalized frequency $V \sim 5.6$ at 1.55 μm, six LP-modes would be guided by a conventional fiber. The second low refractive index trench ($\Delta_2 \sim 0.1\ \%$) is 25 μm away from the fiber axis, and has a ~3 μm width.

The RIP of the fabricated fiber deviates slightly from the fiber proposed in Fig. 1a. The numerical simulations have therefore been performed for the refractive index profile of the exact fiber by using the transfer matrix method [12]. As the fibre structure was slightly elliptical, simulations were performed on RIP taken at right angle to each other across the fiber section. The calculated intensity diameter (at $1/e^2$ of maximum intensity) of the LP_{01} mode has been found to be 26 μm (corresponding to an effective area equal to 530 μm^2). The calculated propagation loss for the LP_{01} modes evaluated on each axis are 3.25 and 1.63 dB/m respectively, whereas the calculated loss for the LP_{11} mode are 56 and 37 dB/m, respectively. All other HOM are expected to suffer higher loss compared to the LP_{11} mode. Therefore, after propagation through a short length of fiber one expects that LP_{11} mode is stripped-off while the LP_{01} mode suffers from nominal loss. Note that the slight ellipticity of the fiber can be corrected by further process optimization, and is not a limitation of the fabrication method to obtain readily cylindrical geometry.

The characterization of the modal properties of the fiber at 1.55 μm was performed by exciting all possible modes with a strongly convergent beam obtained from a fiber pigtailed laser diode and a high numerical aperture lens (60x-microscope objective). The output near-field was observed using another 60x-microscope objective and imaged on a camera. In all intensity profiles the transverse dimensions have been calibrated using the same apparatus and a standard single-mode fiber (SMF, Draka, type G.652.B, mode diameter 10.1 ± 0.5 μm at 1.55 μm). Images and intensity profiles were captured at various lengths of the fiber, using the cut-back method. Some examples are shown in Fig. 2. For 5 cm, the multimode excitation is visible. The intensity profile was extremely sensitive to launching conditions and fiber bending. For longer lengths of the fiber, the profiles became smoother and their sensitivity to launching conditions diminished. For the fiber longer than 2 m, the profile became Gaussian-like, and the launching conditions influenced only the output power and not the profile. The measured $1/e^2$-mode diameter after 4 m propagation was measured to be 22 ± 2 μm (effective area ~380 μm^2), relatively in good agreement with numerical simulations (Fig. 2). Also, good agreement between the measured and simulated mode intensity profiles has been observed. Note that none of the leaky modes are properly guided; therefore no cut-off wavelength is defined.

The propagation loss of the fundamental LP_{01} mode was measured using the multiple cut-back method between 1500 and 1570 nm wavelengths. A fiber pigtailed tunable laser diode was connected to the input of the test fiber. A 4 cm-loop was made on the input end of the fiber to reject more strongly any HOM and therefore preferentially excite the fundamental LP_{01} mode. The output power measurements were done using a power-meter.

The multiple cut-back technique consists of measuring the output power for different fiber lengths (without changing the coupling conditions). The fiber was cut several times (typically 50 to 80 cm) and the output power was measured each time. The starting length was 8.78 m, and the shortest length was 2.0 m, therefore more than ten measurements could be done. The loss coefficient was obtained by fitting the curve of output power versus length with an exponential function. The results are shown in Fig. 3. The loss of the LP_{01} mode increases with the wavelength, from ~1 dB/m at 1500 nm up to 3 dB/m at 1560-1570 nm. The calculated losses of the LP_{01} mode for the RIP at 0˚ and 90˚ are also plotted in Fig.3. It can be seen that the measured values always lie between the calculated values corresponding to the two RIPs. To have significance of departures of measured LP_{01} mode loss from the calculated values, we have also plotted the numerically calculated spectral variation of LP_{11} mode. It can be seen that the departures of LP_{01} mode loss from the calculated values are very small compared to the differential leakage loss between the LP_{01} and LP_{11} modes and does not significantly affect the single-mode operation of the fiber. The measured loss for the LP_{01} mode is higher than acceptable even for a laser or an amplifier. However a more complex structure in the cladding involving a larger number of low-index trenches, and accessible to CVD processes, would lower the confinement loss of the LP_{01} mode, as already shown by numerical simulations. The effective single-mode operation of this fiber, having a very simple RIP structure, is in good agreement with numerical simulations. It is experimentally shown that a large and high NA core can support only the LP_{01} mode after a couple of meters of propagation. A mode effective area of 380 μm^2 was obtained. A more complex version of the RIP, comprising up to four trenches with low-refractive index may allow a mode effective area up to 700 μm^2 together with 40 dB-mode discrimination between LP_{01} and LP_{11} modes [10]. Although the value of accessible mode area is less than state-of-art using complex microstructured leaky fiber, it has potentials for medium power fiber laser, and implements a mature and straightforward manufacturing technique.

Conclusions

We have successfully demonstrated the principle of operation of an MCVD LMA fiber based on higher-order mode discrimination. There are several advantages of this kind of fiber in laser and amplifier applications : low bending loss is achievable thanks to the high numerical aperture of the central core; preforms and fiber are easy to prepare because standard fabrication techniques can be implemented, such as MCVD or OVD; it is possible to dope the core with rare-earth ions for amplification; and the waveguide geometry could be strictly cylindrical for applications where low birefringence is required. Cladding pumping for high power amplification should not be altered by the structured cladding, because the latter would be transparent to short wavelength pump modes. These advantages altogether render this class of single-mode, solid-core, large mode area optical fibers interesting for future applications.

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Figure captions list

Fig. 1: Refractive index profile of the LMA fiber proposed (a), fabricated (b). The ripples observed above 30 µm away from the fiber axis are due to measurement artifacts only.

Fig. 2 : Top: Near-field mode intensity images captured at various lengths of the fiber. Bottom: Mode intensity profiles (crossed symbols: measured from LMA after 4 m, solid line: numerical simulation, dashed line: profile of a standard SMF).

Fig. 3 : Leakage losses of the first two modes of the fiber. The top curve: calculated loss of LP_{11} mode, The bottom curves: calculated losses of LP_{01} mode corresponding to 0˚ and 90˚ RIP. The diamond symbols show the measured loss of LP_{01} mode.

Figure 1 (one column)

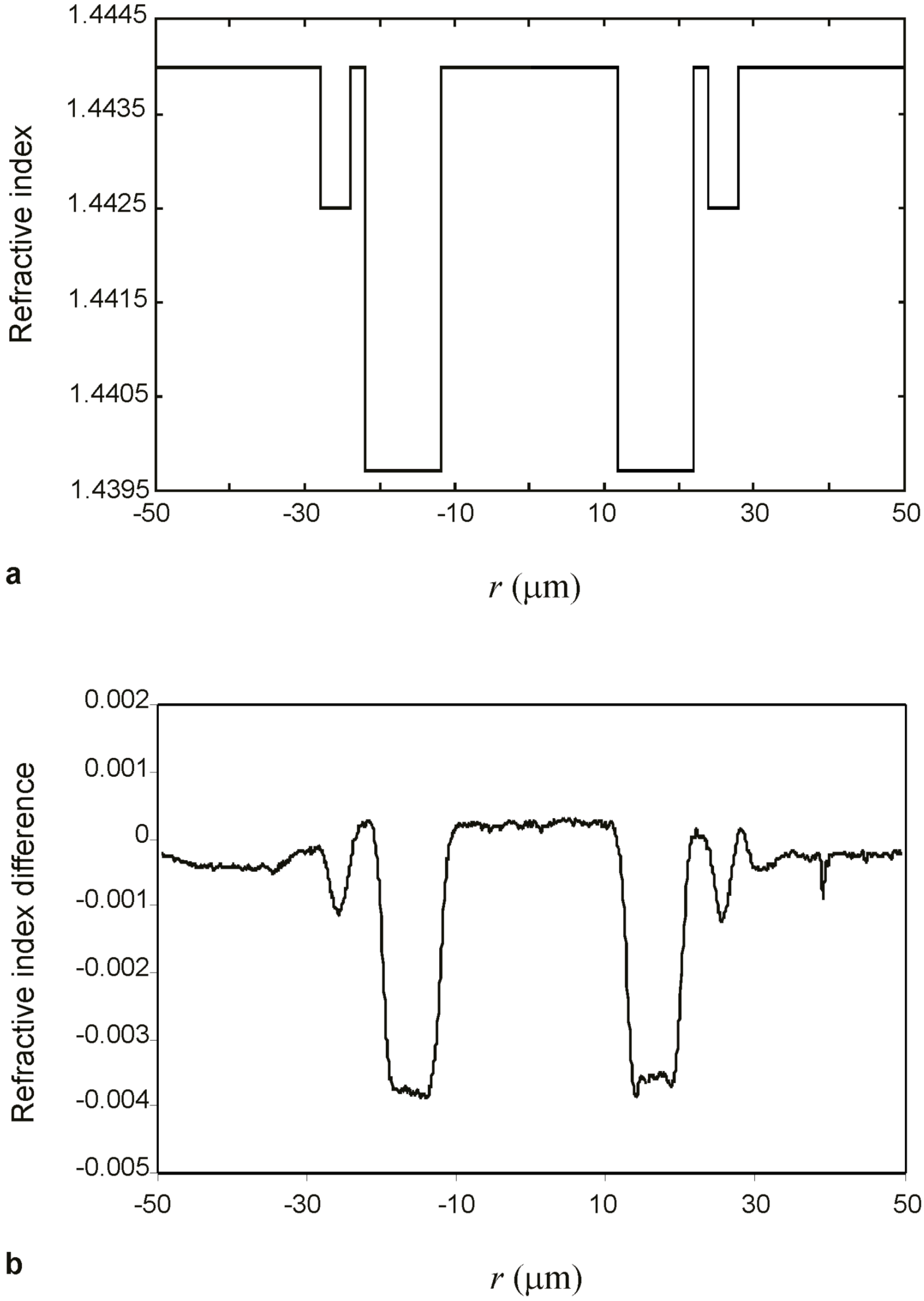
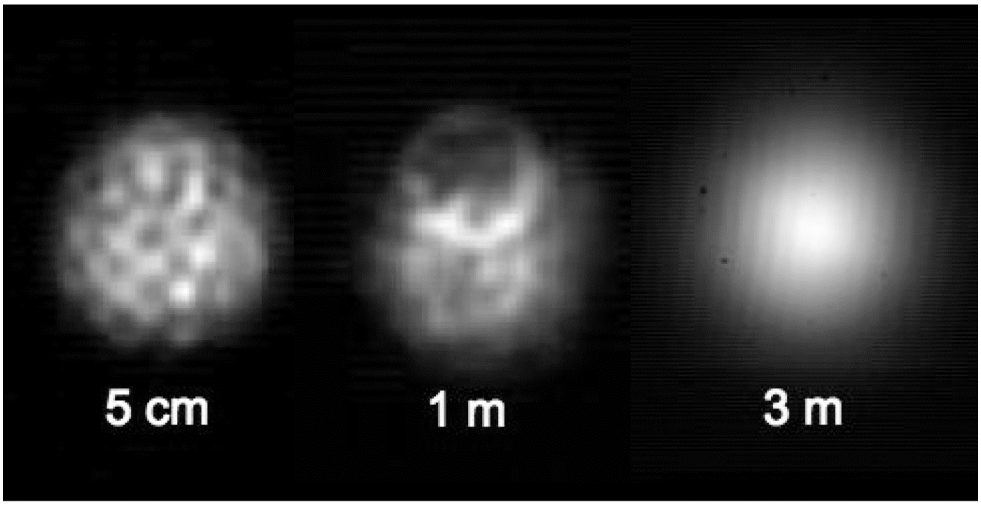


Figure 2 (one column)



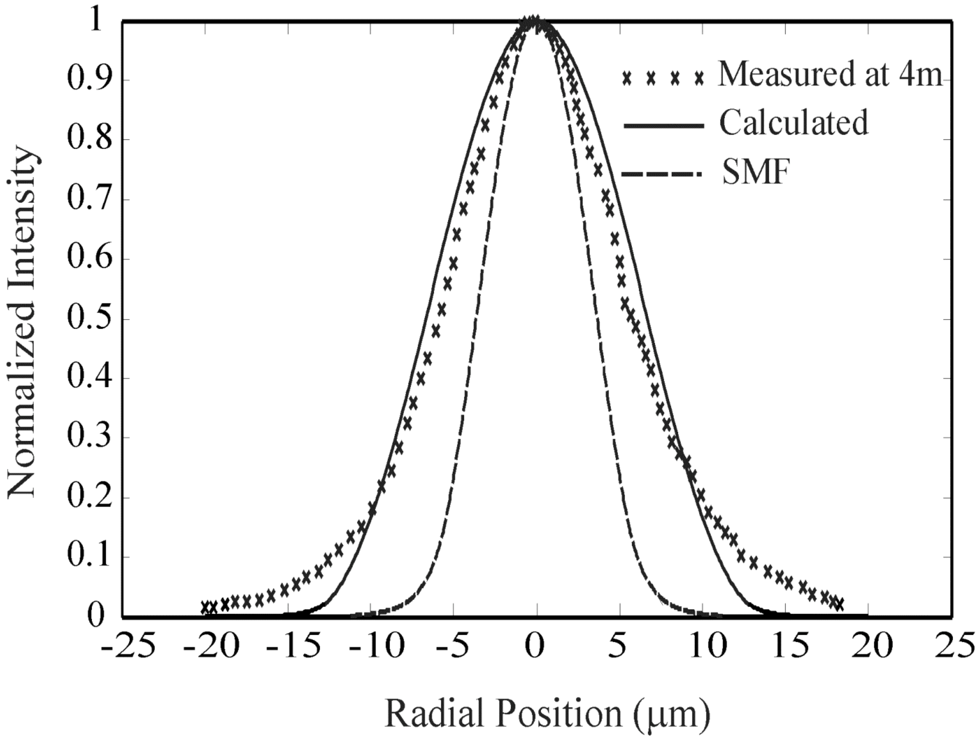


Figure 3 (one column)